VALUE-DRIVEN ATTENTIONAL CAPTURE:

EXPLORING THE INFLUENCE OF REWARD HISTORY ON INVOLUNTARY ATTENTIONAL SELECTION

by

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Abstract

Attention selects stimuli for cognitive processing, and the mechanisms that underlie the process of attentional selection have been a major topic of psychological research for over 30 years. From this research, it has been well documented that attentional selection can proceed both voluntarily, driven by visual search goals, and involuntarily, driven by the physical salience of stimuli. In this dissertation, I provide a conceptual framework for attentional control that emphasizes the need for stimulus selection to promote the survival and wellbeing of an organism. I argue that although goal-driven and salience-driven mechanisms of attentional selection fit within this framework, a central component that is missing is a mechanism of attentional selection that is uniquely driven by learned associations between stimuli and rewards. I go on to present evidence for such a value-driven mechanism of attentional selection, and describe how this mechanism functions independently of the well documented salience-driven and goal-driven mechanisms. I conclude by arguing that reward learning modifies the attentional priority of stimuli, allowing them to compete more effectively for selection even when nonsalient and task-irrelevant.

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Dedication

This dissertation is dedicated to beginnings and endings. My time at Johns Hopkins University marked the beginning of a new and exciting opportunity for me, one that for most of my life never even seemed possible. Within my first couple of months at Hopkins, I celebrated my marriage to my wonderful wife Juliene (Musser) Anderson and I mourned the loss of my beloved grandfather Joseph Rottkamp. My grandfather was one of my strongest advocates, and his encouragement and generosity played an immense role in making a college education a possibility for me. My wife remains my strongest advocate. Standing on the other end of this body of work, I can see the sun setting not only on my time as a PhD student but also on the career of my dear friend and mentor Dr. Steven Yantis, whose gentle and steady hand guided me through my time here. May this document stand as but a small piece of your undying legacy. I do not have the strength to lift your heavy mantle, but I will lift my own in memory of you.

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Chapter I: Introduction and Theoretical Framework

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The external world presents a large amount of information to be processed by an organism. Visual scenes often contain many different objects, each of which is comprised of many component features. Representing these objects and features is a fundamental task of the visual system, as what is represented will then be available for higher-order cognitive processes such as reasoning, decision making, and memory storage.

Given the large amount of information contained in visual scenes, the brain's ability to represent all of this information is severely limited. Stimuli compete for representation in the brain, requiring a process of selection by which selected objects are represented at the expense of others (e.g., Desimone & Duncan, 1995; Reynolds, Chelazzi, & Desimone, 1999). This core mechanism of selection is referred to as selective attention, and it has been the topic of intense investigation for over 30 years.

1. Attentional Priority as a Function of Stimulus Value

Which stimuli are selected by attention has important implications for the survival and wellbeing of an organism. In order for a stimulus to be acted upon, it must first be attended such that it becomes available to resource-limited cognitive systems such as working memory and decision making. Stimuli that are not attended often fail to reach awareness (Mack & Rock, 1998; Most et al., 2001; Rensink, O'Regan, & Clark, 1997). How quickly a stimulus is selected via attention is also of critical importance. By more rapidly attending to a stimulus, individuals maximize the amount of time they have to act upon the stimulus. Failing to rapidly attend to a stimulus may result in a missed opportunity to obtain a reward or to avert a negative outcome.

I argue here that attentional priority reflects the overall value of selecting the different stimuli in an environment. Core mechanisms of computing attentional priority will evolve to the extent that they increase the likelihood that an organism will survive and thrive. More specifically, attentional priority will be computed in such a way that, if the same computations are repeated over many instances, these computations will maximize the rewards and minimize the losses experienced by the organism. Although the attentional priority of a particular stimulus in a particular context will not always be adaptive, the computations that underlie attentional priority will give rise to selection that is as adaptive as possible in the long run.

Two mechanisms of attentional selection have been well defined in the literature: a goal-driven mechanism and a salience-driven mechanism (e.g., Connor, Egeth, & Yantis, 2004; Corbetta & Shulman, 2002). I briefly review each one here, and argue that each is consistent with a value-based framework for the computation of attentional priority. An attentional system optimized to maximize rewards and minimize losses will prioritize both goals and salience in determining which stimuli are selected.

1.1. Goal-Driven Attentional Selection

Our goals are often adaptive. When we are hungry, we search for food. When we know danger may be present, we look for it and try to avoid it. Our goals are also very flexible and can rapidly adapt to changes in expectations and task demands (e.g., Anderson & Folk, 2012a, 2014; Lien, Ruthruff, & Johnston, 2010). Thus, it would seem useful for an adaptive system of attentional control to be able to factor ongoing goals into the computation of attentional priority.

A wealth of research demonstrates that currently active goals play a powerful role in computing attentional priority. Attention can be deployed to a particular location when individuals are cued in advance to attend to that location in preparation for an upcoming

target (e.g., Posner, 1980). Such deliberate attention allocation can greatly reduce distraction by stimuli outside of the focus of attention (Yantis & Johnston, 1990). Goal-driven attentional control can also operate through the prioritization of stimulus features. Knowledge of the specific features of the upcoming target increases the efficiency of visual search, such that attentional selection can be largely restricted to stimuli that possess a target-defining feature (Egeth, Virzi, & Garbhart, 1984; Wolfe, Cave, & Franzel, 1989; Wolfe, 1994).

Goal-driven attentional selection is at times voluntary and deliberate, but may proceed rapidly and automatically as well. When the target of visual search is known in advance, stimuli that possess a target-defining feature capture attention. This is referred to as contingent attentional capture (Folk, Remington, & Johnston, 1992). Distractors that share the defining feature of the target selectively produce a spatial cuing effect consistent with attentional selection (Anderson & Folk, 2010, 2012b; Folk & Anderson, 2010; Folk, Leber, & Egeth, 2002; Folk & Remington, 1998; Folk et al., 1992). This goal-related selectivity in attentional selection is further supported by eye movement measures (Ludwig & Gilchrist, 2002, 2003) and neurophysiological indices of stimulus processing (e.g., Eimer & Kiss, 2008; Serences et al., 2005; Serences & Yantis, 2007). Contingent attentional capture is adaptive in that it rapidly orients attention to likely targets, facilitating more rapid target localization, at the possible expense of selecting feature-similar nontargets that need to be rejected. It reflects a hybrid form of voluntary and involuntary attentional control—the instantiation of the goal state is voluntary, while the allocation of attention that follows is not.

1.2. Salience-Driven Attentional Selection

Our goals will not always encapsulate what is relevant to our survival in a given context. Opportunities and dangers that we do not expect may suddenly present

themselves, such as a predator leaping out from hiding. In addition, goal-directed attentional control is cognitively demanding to maintain, and individuals experience periodic lapses in the ability to efficiently carry out deliberate visual search (Leber, Turk-Browne, & Chun, 2008; Leber, 2010; Lechak & Leber, 2012). A mechanism of attentional selection that can function independently of ongoing goals would be adaptive provided that the benefits of having attention automatically captured outweigh the cost of potential for distraction from goal-directed processing.

Attentional selection is influenced by physical stimulus salience. Visual search for a target is slowed by the presence of a physically salient nontarget (Theeuwes, 1991, 1992, 1994, 2010; Yantis & Jonides, 1984), which involuntarily draws eye movements (e.g., Theeuwes, de Vries, & Godijn, 2003; Van der Stigchel & Theeuwes, 2005). Computational models that can account for the search behavior of observers place a strong emphasis on the physical salience of stimuli (e.g., Itti & Koch, 2001). The capture of attention by physically salient stimuli is also supported by neurophysiological measures that show preferential processing of a salient distractor (e.g., Hickey, McDonald, & Theeuwes, 2006; but see McDonald, Green, Jannati, & Di Lollo, 2013).

The extent to which salience-driven attentional priority can be overridden by goal-driven attentional control is currently a matter of debate. Physically salient stimuli that do not match a currently active target template have consistently failed to produce evidence of attentional capture using both behavioral (e.g., Folk et al., 1992; Folk & Remington, 1998) and neurophysiological measures (Eimer & Kiss, 2008, 2010; Lien, Ruthruff, Goodin, & Remington, 2008). Salient but task-irrelevant stimuli most robustly capture attention when the features of the upcoming target cannot be anticipated (e.g., Bacon & Egeth, 1994; Folk & Anderson, 2010), suggesting that goal-driven attentional control may be capable of gating the influence of salience on attentional selection. However, this position is not without

controversy (see Acta Psychologica, vol 135*(2)*, for a review and commentary), and whether goals or salience play the more dominant role in determining which stimulus is selected via attention remains a contested issue (e.g., Anderson & Folk, 2012b; Belopolsky, Schreij, & Theeuwes, 2010; Sawaki & Luck, 2010; Theeuwes, 2010).

Salient visual events can carry important information concerning potential reward availability or danger. The abrupt appearance of a new object is highly attention grabbing (Yantis & Hillstrom, 1994), and rapidly assessing this event in order to plan a response, if appropriate, would be beneficial for an organism. The temporary distraction from goal-directed processing caused by attentional capture is often very brief (e.g., Theeuwes, 1991, 1992) and can be contrasted with the potential cost of missing an opportunity to procure an available reward or escape danger, particularly when the opportunity is fleeting. Computational modeling suggests that a bias for attending to salient stimuli can serve in the interest of maximizing overall reward procurement (Laurent, 2008).

1.3. Beyond Salience and Goals

So far, I have argued that mechanisms for computing attentional priority serve in the interest of maximizing rewards and minimizing losses, and that salience-driven and goal-driven mechanisms of attentional selection are consistent with this framework. But are these two mechanisms sufficient to satisfy the requirements of a system built to secure the survival and wellbeing of an organism? I propose that an adaptive system of attentional selection must also be understood in terms of the influence of prior reward learning. Reward-related stimuli will not always be physically salient, nor will an organism always be searching for a particular reward-related stimulus when it is encountered. An attentional system that only factors goals and salience into the computation of priority for selection is likely to result in missed opportunities to obtain a reward or escape danger, as both goals and salience are only indirectly related to the value of a stimulus. If the computation of

attentional priority is truly rooted in maximizing rewards and minimizing losses, this would predict a direct influence of the learned value of stimuli on selection, such that stimuli that have been learned to predict reward compete for selection regardless of their salience and goal-relevance.

2. Evidence that Attentional Selection is Shaped by Rewards

Here, I review recent evidence that attentional selection can be shaped by the reward structure of the environment. Ecologically pertinent stimuli have high priority for attentional selection, attention is biased to select stimuli associated with reward, and attentional selection can be primed by recent reward feedback. The implications of these results, both in terms of our understanding of mechanisms of attentional selection and in terms of the proposed framework, are then discussed.

2.1. Ecologically Pertinent Stimuli Capture Attention

Certain stimuli that are particularly important to promoting survival and wellbeing have been shown to have high attentional priority. For example, socially relevant stimuli capture attention (e.g., a happy face, Hodsoll, Vinding, & Lavie, 2011), as do sexually relevant stimuli (e.g., a naked body, Most, Smith, Cooter, Levy, & Zald, 2007). Although this provides evidence of involuntary attentional capture by valuable stimuli, the mechanisms that underlie such attentional selection are unclear. One potential explanation for the high attentional priority of ecologically pertinent stimuli is that they have acquired learned value through repeated pairings with reward, and it is this representation of learned value that is driving attention. At the same time, however, such effects can also be explained by mechanisms that do not implicate learning. For example, a bias to attend to socially relevant stimuli is evident from infancy (e.g., Farroni, Csibra, Simion, & Johnson, 2002; Farroni et al., 2005; Franz, 1961), consistent with an inherited attentional bias that precedes learning. Because of this ambiguity, the remainder of the studies I review in this section employ

methodologies in which the stimulus–reward associations that underlie observed attentional biases are experimentally controlled.

2.2. Reward Modulates Efficiency of Selection in Visual Search

Selection processes in visual search are influenced by stimulus–reward associations. Selection of a target amongst nontargets is more efficient when the target is associated with the delivery of a reward (e.g., Kiss, Driver, & Eimer, 2009; Kristjansson, Sigurjonsdottir, & Driver, 2010). Even with complex reward structures, individuals are able to allocate attentional priority to different targets in order to maximize total reward procurement (Navalpakkam, Koch, & Perona, 2009; Navalpakkam, Koch, Rangel, & Perona, 2010). When stimulus selection is rewarded, individuals make more efficient use of cue information to restrict attentional processing (Pessoa & Engelmann, 2010). Such effects of reward on attention can be explained by reward operating through the enhancement of goal-directed control, reflecting motivated performance.

Evidence from human functional magnetic resonance imaging (fMRI), psychophysics, and single unit recording in rats and monkeys further supports the notion that associations with reward modulate the attentional priority of stimuli. The response to a stimulus in early visual areas can be predicted from the recent reward history of that stimulus, and this response adapts to reflect changes in experienced reward (Serences, 2008). Orientation tuning becomes sharper for orientations that are associated with reward outcome (Serences & Saproo, 2010), a process that can proceed even without conscious awareness (Seitz, Kim, & Watanabe, 2009). When a stimulus is learned to predict high reward, it persistently evokes increased activity in the lateral intraparietal area (area LIP) (Peck, Jangraw, Suzuki, Efem, & Gottlieb, 2009), and stimulus-evoked activity in area V1 of the visual cortex reflects the anticipated timing of the receipt of reward (Shuler & Bear, 2006).

Learned stimulus–reward associations have been further shown to affect subsequent attentional selection. In one study, participants learned to associate different faces with different monetary reward outcomes in a training phase, and these faces later appeared as targets in a subsequent attentional blink task. Faces previously associated with high monetary gains or losses were more accurately reported than other faces when presented as the second of two targets, suggesting that they had higher attentional priority (Raymond & O'Brien, 2009). In a similar study reported by Della Libera and Chelazzi (2009), stimuli previously associated with high and low rewards could appear as both targets and nontargets in a subsequent object identification task. Stimuli previously associated with high reward were more rapidly identified as targets and more slowly rejected as distractors, while the opposite was true for stimuli previously associated with low reward (see also Della Libera, Perlato, & Chelazzi, 2011).

Reward-motivated attentional priorities can also influence the selection of task-irrelevant stimuli in much the same way that task goals influence selection in contingent attentional capture. Participants engaged in a Stroop task in which quickly and accurately naming particular colors was met with a monetary reward. These rewarded colors were named more quickly than other, non-rewarded colors, indicating that attentional priorities for the colors reflected the reward structure (Krebs, Boehler, & Woldorff, 2010). Importantly, words that named a reward-associated color produced greater response time interference than other color-words, which was further supported by associated increases in neural activity in the presupplementary motor area as revealed through human fMRI (Krebs, Boehler, Egner, & Woldorff, 2011).

2.3. Reward Primes Attentional Selection

When a stimulus is selected on a given trial, the selection of that stimulus is facilitated on subsequent trials, a phenomenon referred to as inter-trial priming or priming

of pop-out (e.g., Belopolsky et al., 2010; Folk & Remington, 2008; Found & Müller, 1996; Müller, Heller, & Ziegler, 1995; Müller, Reimann, & Krummenacher, 2003; Kristjansson & Campana, 2010; Maljkovic & Nakayama 1994; Theeuwes & Van der Berg, 2011). In inter-trial priming, recently selected stimuli are more rapidly identified as targets and are more slowly rejected as distractors. Recent evidence shows that inter-trial priming is modulated by the extent to which the selection of a stimulus was recently rewarded.

In the first study to assess reward-modulated priming, Della Libera and Chelazzi (2006, Experiment 1) employed a global-local number identification task pioneered by Navon (1977). Participants were shown a large number (global feature) comprised of identical smaller numbers (local features) on a given trial (e.g., a large 7 made up of small 2's), and were cued in advance which feature to perform an identity judgment on. Participants were randomly given a high or low monetary reward for correctly identifying the cued feature. These were referred to as prime trials, each of which was followed by an unrewarded probe trial on which only one of the two features could be mapped onto a response (e.g., a large 6 made up of small X's). Following a high reward, response time was faster on probe trials when the judgment from the prime trial was repeated and slower when the judgment switched, consistent with inter-trial priming of the rewarded feature. This pattern was reversed, however, following the receipt of a low reward, suggesting that participants were biased *against* repeating the same judgment in this case. A follow-up experiment reported the same reward-dependent pattern of priming when the color of stimuli was primed in an object discrimination task (Della Libera & Chelazzi, 2006, Experiment 2).

In another important study on reward-modulated priming, Hickey, Chelazzi, and Theeuwes (2010a) employed a paradigm in which participants performed visual search for a shape singleton target (e.g., diamond among circles). On some of the trials, one of the

nontarget shapes was presented in a unique color, which served as a physically salient singleton distractor (e.g., a red shape among green shapes). Participants were randomly given a high or low reward for correctly identifying the shape singleton target on a given trial. Critically, the color of the target and distractor could either be repeated or swapped on the subsequent trial, allowing for the assessment of inter-trial priming of color and its relation to prior reward. The results were very similar to those reported by Della Libera and Chelazzi (2006) in that priming was again dependent on reward feedback—large priming effects were observed following high reward that were reversed or eliminated following low reward. The magnitude of the extent to which reward modulated priming in this way was well predicted by reward-evoked activity in anterior cingulate cortex (Hickey et al., 2010a).

A follow-up study revealed that the magnitude of reward-modulated priming across individuals is positively correlated with individual reports of the extent to which reward motivates behavior (Hickey, Chelazzi, & Theeuwes, 2010b). Thus, individuals who are the most motivated by rewards are also the most influenced by recent reward history in visual search. Reward modulated priming was also shown to be specific to stimuli whose selection as a target was associated with reward (Hickey, Chelazzi, & Theeuwes, 2011) and is evident in eye movement trajectories in addition to covert attention allocation (Hickey & van Zoest, 2012).

Accounts of attentional control have been forwarded that explain distractor suppression in terms of an individual's motivation to suppress visual features (e.g., Geyer, Müller, & Krummenacher, 2008; Moher, Abrams, Egeth, Yantis, & Stuphorn, 2011; Müller, Geyer, Zehetleitner, & Krummenacher, 2009). One possible account of reward-modulated priming is that reward feedback dynamically adjusts an individual's incentive to suppress the prior target feature on a trial-by-trial basis, leading to more or less attentional capture

as a function of prior reward. There are several aspects of reward-modulated priming that suggest it is to some degree independent of such voluntary influences on attention. Reward-modulated priming occurs despite the fact that the rewards are completely unrelated to task performance, a design element that participants are informed of (Hickey et al., 2010a, 2010b, 2011). Furthermore, reward-modulated priming persists even when observers are provided with direct incentive to search for the non-primed feature on the following trial (Hickey et al., 2010a), suggesting that reward-modulated priming is resistant to countermanding goal-driven attentional control. Brain circuits involved in reward processing and incentive motivation are believed to be interrelated (e.g., Berridge, 2012; Berridge & Robinson, 1998); this suggests that the experience of reward may modulate the incentive salience of a stimulus in an automatic fashion.

3. Exploring the Role of Reward History in Involuntary Attentional Selection

An important prediction of the framework I have proposed is that the learned value of a stimulus should bias attentional selection independently of the physical salience and goal-relevance of the stimulus, such that previously reward-associated stimuli compete for selection even when nonsalient and task-irrelevant. Up to this point, the extent to which attentional priority is modulated specifically by learned stimulus–reward associations is unclear. The receipt of reward clearly modulates stimulus priming, but such an effect cannot be attributed to a learned association. In reward-modulated priming, attentional priority is biased by the actual receipt of reward (Hickey et al., 2010a), such that the attentional priority of reward-related stimuli constantly fluctuates based on their most recent reward history (Della Libera & Chelazzi, 2006; Hickey et al., 2010a, 2010b, 2011).

Although the effects of stimulus–reward associations on search efficiency are consistent with a direct and involuntary effect of learned value on selection, they may also reflect the contribution of reward motivating the voluntary, goal-directed control of

attention. Attending to reward-related stimuli and procuring rewards often represent explicit goals of the task in studies on reward and attention (Maunsell, 2004). Indeed, in all of the aforementioned studies on how reward modulates selection in visual search, the reward-associated stimuli (1) could appear as a sought target or otherwise provided information about the target and/or (2) could appear when performance was still motivated by currently available rewards. One possibility, then, is that the influence of learned stimulus–reward associations on attentional priority is subsumed entirely within the domain of voluntary, goal-driven attentional control. In this sense, reward merely acts to strengthen goal-directed attentional control through mechanisms of motivation. By such an account, learned stimulus–reward associations have no specific role in modulating attentional priority.

In the chapters that follow, I present experiments that directly assess the role of learned stimulus–reward associations in involuntarily driving attentional selection. In this series of studies, I tested whether stimuli that have been previously associated with reward through learning involuntarily capture attention even when entirely task-irrelevant and when rewards are no longer available. That is, I compared the attentional priority of irrelevant stimuli that differed only in their prior history with reward. The results indicate a uniquely value-driven mechanism of attentional control that functions independently of salience-driven and goal-driven mechanisms.

Chapter II: Salience-driven Attentional Capture is Modulated by Reward History

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Effective deployment of attention is critical to the successful performance of any cognitive task. Attention determines what aspects of the sensory input are selected for cognitive processing, memory storage, and awareness. Two modes of attentional control are widely believed to determine perceptual priority: a voluntary, goal-directed mode, in which attention is guided by contextually appropriate goals and intentions, and an involuntary, stimulus-driven mode, in which attention is captured by physically salient stimuli (Corbetta & Shulman, 2002; Itti & Koch, 2001; Theeuwes, 1992, 2010) or by task-irrelevant stimuli that share identifying features with a searched-for target (Anderson & Folk, 2010; Folk et al., 1992). Each of these modes of control present concomitant benefits and costs: voluntary control of attention is goal-specific but potentially slower to implement; involuntary attentional capture can rapidly orient the organism to unexpected changes that could signal danger or opportunity, but has the potential to cause distraction from intended acts of perception.

Goal-directed and stimulus-driven modes of attentional control have long been a focus of intense investigation, and much has been learned about the operating principles of each mode of control and their interaction (Corbetta & Shulman, 2002; Theeuwes, 2010). However, there is growing evidence that these are not the only influences on attentional deployment. To promote survival and wellbeing, the brain is optimized to learn about perceptual stimuli that signal the potential for procuring reward (Shuler & Bear, 2006; Seitz et al., 2009). Voluntary attention to stimuli that predict reward is an effective mechanism

for efficiently selecting valuable stimuli (Maunsell, 2004). Many studies have shown that reward facilitates voluntary attention to task-relevant stimuli, and that reward-based strategies and priorities strongly influence attentional performance (Della Libera & Chelazzi, 2006, 2009; Hickey et al., 2010a, 2010b, 2011; Krebs et al., 2010; Navalpakkam et al., 2010; Peck et al., 2009; Pessoa & Engelmann, 2010; Raymond & O'Brien, 2009; Serences, 2008; Serences & Saproo, 2010).

Attentional capture by valuable but task-irrelevant stimuli could also confer adaptive advantages in many circumstances, leading the perceiver to orient to inconspicuous and/or unexpected reward-related stimuli. At the same time, however, attentional capture by reward-related stimuli (e.g., drugs of abuse, excessive food, or even irrelevant but rewarding information like an email chime) can be maladaptive when it conflicts with contextually appropriate goals (e.g., intended abstinence from a drug or food) (Bush, 2010; Davis, 2010; Field & Cox, 2008; Garavan & Hester, 2007; Robinson & Berridge, 2008). This raises the possibility that valuable stimuli capture attention involuntarily as a consequence of reward learning. In this chapter, I provide the first test of the hypothesis that learned value automatically guides attentional selection.

1. Experiment 1

Human participants first learned stimulus–reward associations in a training phase involving visual search for color-defined stimuli (Figure 1a); correct responses in target identification were followed by monetary reward feedback, and one target color was associated with a larger reward than the other on average. Immediately following the training phase, participants completed a test phase in which color was irrelevant to the task and previously reward-associated color stimuli were occasionally presented as task-irrelevant distractors (Figure 1b).

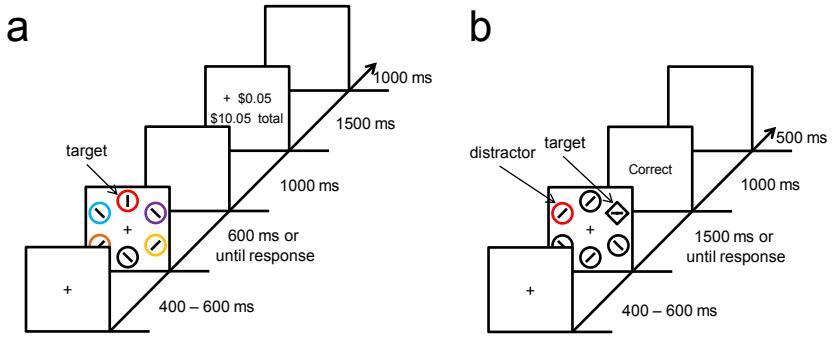


Figure 1. Sequence and time course of trial events. **(A)** Targets during the training phase were defined by color (red or green, exactly one of which was present on each trial), and participants reported the identity of the line segment inside of the target (vertical or horizontal) with a key press. Correct responses were followed by the delivery of monetary reward feedback. One of the target colors was followed by a high reward on 80% of the trials and a low reward on 20% of the trials; for the other target color, this mapping was reversed. **(B)** During the test phase, the target was defined as the unique shape, and no reward feedback was provided. On half of the trials, one of the non-target items—the distractor—was rendered in the color of a formerly rewarded target (each color equally often).

The distractors in the test phase were physically salient color singletons, which are known to robustly capture attention as a consequence of their feature contrast when the target is also salient (e.g., Bacon & Egeth, 1994; Theeuwes, 1992, 2010). My primary focus here was to determine whether a salient high-value distractor would capture attention more robustly than a salient low-value distractor. If learned value has no automatic influence on attention, then high- and low-value color singletons should produce similar slowing in visual search. If learned value combines with physical salience in the guidance of attention, then the formerly high-reward distractors should slow responses more than formerly low-reward distractors.

1.1. Methods

1.1.1. Participants. Eighteen participants were recruited from the Johns Hopkins University community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were provided monetary compensation that varied between $21 and $28 (mean = $25.22), depending on their accuracy. All participants read and signed

an informed consent form prior to participating in the experiments. The study was approved by the Johns Hopkins University Institutional Review Board.

1.1.2. Apparatus and Stimuli. A Mac Mini equipped with Matlab software and Psychophysics Toolbox extensions was used to present the stimuli on a Dell P991 monitor. The participants viewed the monitor from a distance of approximately 50 cm in a dimly lit room.

The sequence of events and time course for the training and test phases are shown in Figure 1a and 1b, respectively. Each trial consisted of three displays: a fixation display, a search display, and a feedback display. During both the training and test phases, the fixation display consisted of a white fixation cross (.5° x .5° visual angle) presented in the center of the screen against a black background, and the search display consisted of the fixation cross surrounded by six shapes (2.3° x 2.3° visual angle) placed at equal intervals along an imaginary circle with a 5° radius.

1.1.2.1. Training Phase. During the training phase, the six shapes that comprised the search display were all circles of different colors (red, green, blue, cyan, pink, orange, yellow, and white). Targets were defined as either a red or green circle, one of which was presented on every trial in a randomly-selected location. Inside the target shape, a white line segment was oriented either vertically or horizontally, and inside each of the nontarget shapes, a white line segment was tilted at 45° to the left or to the right. The feedback display informed participants of the reward earned on the current trial, as well as total reward accumulated thus far.

1.1.2.2. Test Phase. During the test phase, the search display consisted of a white circle among white diamonds or a white diamond among white circles, and the target on each trial was defined as the unique shape. On a randomly-selected half of the trials, one of the nontarget elements, the *distractor*, was rendered in red or green (equally often). The

feedback display at test only informed participants whether their response on the current trial was correct.

1.1.3. Design

The experiment consisted of a single session of 1008 training trials followed by 480 test trials. Participants were provided with 50 practice trials prior to the training phase, and 20 practice trials prior to the test phase. After every 100 trials and between the two phases, participants were provided with a short break. Target identity, target location, distractor color, and distractor location were fully crossed and counterbalanced, and trials were presented in a random order.

Correct responses in the training phase were followed by visual feedback indicating monetary reward. High-reward targets were followed by high-reward feedback (5¢) on 80% of trials and low-reward feedback (1¢) on the remaining 20%; for low-reward targets, the percentages were reversed. High-reward targets were red for half of the participants, and green for the other half. No reward feedback was provided during the initial practice block, and no reward feedback was provided during the test phase. Upon completion of the experiment, participants were given the cumulative reward they had earned.

1.1.4. Procedure

Each participant performed the experiment individually over the course of a single two-hour session. Each session took place inside a dimly lit laboratory room. The experimenter familiarized all participants with each task by providing written and oral descriptions of the stimuli and procedures. Participants were instructed to respond "as quickly as possible while minimizing errors."

Each trial began with the presentation of the fixation display for a randomly varying interval of 400, 500, or 600 ms. The search display then appeared and remained on screen until a response was made or the trial timed out. The training task was performed under

time pressure, with trials terminating after 600 ms; during test, time pressure was lifted by lengthening this time limit to 1500 ms.

Participants made a forced-choice target identification by pressing the "z" key when the line inside the target was oriented vertically and the "m" key when the line inside the target was oriented horizontally. Response time (RT) was measured from the onset of the target display until a response was made or the trial timed out. The computer emitted a 500 ms 1000 Hz feedback tone to inform the participant when a trial timed out. Only correct responses were included in the analysis, and all RTs more than three standard deviations above and below the mean of their respective conditions were excluded from the analysis.

1.2. Results and Discussion

During training, mean RT to high- and low-reward targets did not differ significantly, although there was a trend toward faster responses to the target color associated with high reward, suggesting increased attentional priority, mean difference = 3.4 ms, $t(17) = 1.57$, $p = .135$. To assess how the effect of reward on target selection changed over the course of the training phase, I analyzed the data from the training phase separately in ten bins of roughly 100 trials each. There was no interaction between reward and trial bin, $F(9,153) = 1.43$, $p = .179$, indicating that the influence of reward on RT did not change significantly over time. The main effect of trial bin was significant, $F(9,153) = 4.92$, $p < .001$, $\eta_p^2 = .224$, however, showing that participants generally responded faster with more experience. The data for the training phase are presented in Figure 2.

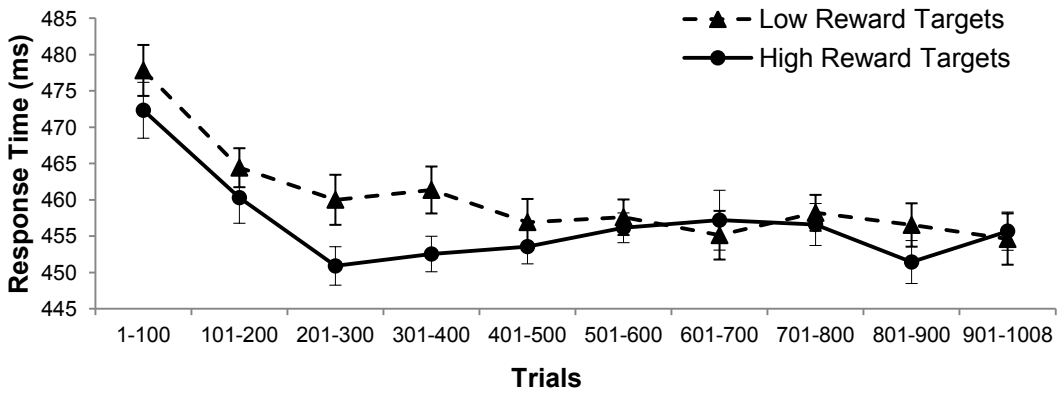


Figure 2. Mean response time ± within-subjects s.e.m. for high- and low-reward targets over the course of the 1008 trials of the training phase.

Of particular interest were the data from the test phase. Reward-color mapping (i.e., red vs. green as the high-reward color in the training phase) did not interact with the effect of value on performance in the test phase, $F < 1$, so further analyses collapsed across color. Response times (RTs) in the test phase differed significantly in the three distractor conditions, $F(2,34) = 48.57$, $p < .001$, $\eta_p^2 = .741$ (Figure 3). Planned comparisons confirmed that both the high-value and low-value distractors slowed RT compared to when no distractor was presented, $t(17) = 8.45$, $p < .001$, $d = 1.99$, and $t(17) = 6.31$, $p < .001$, $d = 1.47$, respectively. This replicates many previous demonstrations of attentional capture by irrelevant but physically salient feature singletons (e.g., Theeuwes, 1992, 2010).

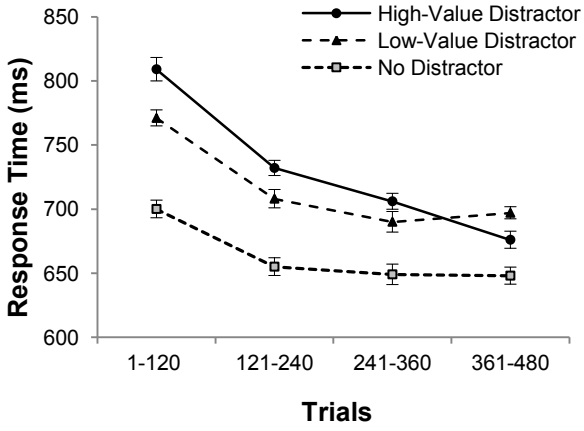


Figure 3. Mean response time ± within-subjects s.e.m. for each distractor condition over the course of the test phase of Experiment 1.

I next examined the effect of reward history on performance in the test phase. High-value distractors slowed RT significantly more than did low-value distractors, $t(17) = 3.37$, $p = .004$, $d = .81$. This modulation of attentional capture by reward history cannot be attributed to differences in physical salience, and occurred despite the irrelevance of the color items to the shape-search task. To assess how the effect of reward history on attentional capture changed over the course of the test phase, I analyzed the data from the test phase separately in four equally-sized 120-trial bins. The effect of learned value on performance gradually extinguished over the course of the unrewarded test trials, as revealed by a linear trend in the difference between RTs for high- and low-value distractor trials over trial bin, $F(1,17) = 17.22$, $p = .001$, $\eta_p^2 = .503$. There was no significant difference in error rates between the three distractor conditions, $F < 1$ (Table 1).

Table 1. Response times (in milliseconds) and error rates by distractor condition for Experiments 1 and 2. Error terms, in parentheses, reflect the within-subjects s.e.m.

Distractor Condition in Experiment 1			**Distractor Condition in Experiment 2**		
None	Low-Value	High-Value	None	Non-Target Colored	Target Colored
655(5.5)	710(3.9)	728(3.8)	588(3.6)	632(4.1)	634(4.8)
.09(.003)	.10(.004)	.10(.005)	.11(.003)	.13(.005)	.13(.005)

These results reveal that learned value magnifies attentional capture by salient stimuli. As the learned stimulus-value associations extinguished in the absence of reward, so did the effect of reward history on performance. However, extinction occurred gradually over many trials, resulting in a robust effect of prior reward on involuntary attention allocation for the first several hundred trials of the test phase. Taken together, these results provide strong evidence that learned value can magnify the effect of physical salience on attentional priority.

2. Experiment 2

Despite the fact that attentional capture in Experiment 1 was significantly modulated by value, it could be that the effect of value on salience-based attentional capture was not critically dependent upon a learned association between stimuli and prior reward. Instead, it is possible that participants continued to maintain a search set for the training-phase target colors, and particularly for the previously high-reward color, even in the test phase. Although it is known that participants can rapidly adjust task-related attentional priorities with changing task demands (Anderson & Folk, 2012a, 2014; Lien, Ruthruff, & Johnston, 2010), former targets can continue to draw attention under certain conditions (Kyllingbaek, Schneider, & Bundesen, 2001; Shiffrin & Schneider, 1977). Thus, it is important to rule out this possible explanation of my results.

I tested eighteen new participants who engaged in a training phase that was similar to that used in Experiment 1, with two critical differences. First, no reward feedback was provided during training or at any point during the experiment; instead, participants were compensated with a flat rate that matched the average earnings of participants in the main experiment ($25). Second, targets were now either red or blue (with green occurring as one of the nontargets) for half of the participants, and green or blue (with red occurring as one of the nontargets) for the other participants. The test phase for all participants was identical to that of Experiment 1. Thus, in the test phase, one color-singleton distractor had been a target color during the training phase, and the other color-singleton distractor had always been a nontarget color. If persisting priority for a former target color alone drove the main findings from Experiment 1, we would expect an equally large—or indeed even larger—difference in RT on trials containing the color distractor that was used as a target during training versus trials containing the color distractor that was never used as a target during training.

2.1. Methods

2.1.1. Participants. Eighteen new participants were recruited from the Johns Hopkins University community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were compensated with $25.

2.1.2. Apparatus and Stimuli. The apparatus and stimuli were identical to Experiment 1 with the following exceptions. Targets during training were either a blue or green circle (for half of the participants), or a blue or red circle. On half of the trials containing each target color, one of the nontarget-colored items was colored either red (for participants searching for green and blue targets) or green (for participants searching for red and blue targets). The feedback display during training only informed participants whether their previous response was correct.

2.1.3. Design and Procedure. The design and procedure were identical to Experiment 1, with the exception that no monetary reward feedback was provided.

2.2. Results and Discussion

Distractors at test were classified as being either the color of a former target or the color of a former nontarget. During the test phase, responses were significantly slowed by both former target-colored and former nontarget-colored distractors, $t(17) = 7.27$, $p < .001$, $d = 1.71$, and $t(17) = 6.13$, $p < .001$, $d = 1.44$, respectively (Figure 4). However, I observed no difference in RT between those two distractor conditions, $t(17) = 0.34$, $p = .740$ (Table 1). The magnitude of slowing caused by the former target color distractors did not decrease over the course of the test phase, $F < 1$, in contrast to Experiment 1. As in Experiment 1, there was no significant difference in error rates among the three conditions, $F(2,34) = 2.20$, $p = .127$ (Table 1).

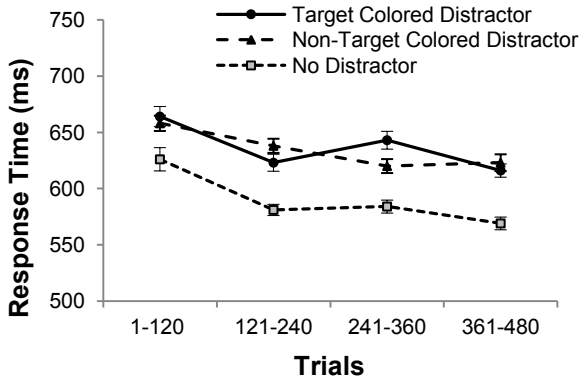


Figure 4. Mean response time ± within-subjects s.e.m. for each distractor condition over the course of the test phase of Experiment 2.

The slowing caused by the high-value distractor in Experiment 1 was significantly greater than that caused by the former target-colored distractor in Experiment 2, mean difference = 27 ms, $t(34) = 2.29$, $p = .025$, $d = .79$. The low-value distractor in Experiment 1 also produced a greater degree of slowing than the former target-colored distractor in Experiment 2, although this difference was not significant, mean difference = 9 ms, $t(34) = 0.80$, $p = .428$. This outcome demonstrates that value associations are necessary to produce the modulation of distraction observed in Experiment 1, and that this modulation cannot be explained merely in terms of a persisting intention to search for former targets.

3. Summary and General Discussion

It is well established that physical salience and ongoing task goals influence attentional priority involuntarily (e.g., Folk et al., 1992; Theeuwes, 1992). Although salience-based and contingency-based mechanisms of attentional control are known to jointly influence attentional priority, it was unknown whether attentional priority can be modulated by learned value. In this chapter, I show that the physical salience and learned value of a stimulus have a combined effect on attentional priority, with learned value increasing attentional priority above and beyond the level afforded by salience alone.

My results demonstrate that a salient but otherwise neutral stimulus, when previously associated with high reward, magnifies distraction even after that stimulus no longer predicts reward. This finding cannot be attributed to differences in physical salience, and Experiment 2 rules out persisting intention to search for a former target as an explanation. The findings provide the first evidence that the learned value of visual stimuli has an involuntary and automatic influence on attentional processing.

Chapter III: Attentional Capture Driven by Learned Value

Material from this chapter was originally published in:
Anderson, B. A., Laurent, P. A., & Yantis, S. (2011b). Value-driven attentional capture. *Proceedings of the National Academy of Sciences, USA, 108*, 10367-10371.

Chapter II showed that physically salient stimuli previously associated with high reward capture attention more robustly than equally salient stimuli previously associated with a comparatively smaller amount of reward. There are multiple mechanisms through which value and salience might be combined in order to jointly determine attentional priority in this way. One is that learned value directly modulates the visual salience or pertinence (Bundesen, 1990) of reward-associated stimulus features, thereby increasing their attentional priority. This possibility is supported by evidence showing that reward-associated stimulus features are represented more robustly in early visual areas of the brain (Serences, 2008; Serences & Saproo, 2010). Furthermore, Navalpakkam and colleagues (2010) showed that attentional selection can reflect an optimal weighting of the conspicuity of a stimulus afforded by its physical salience and its current reward value, suggesting that value-based and salience-based attentional priority can be independently adjusted. Another possibility is that the learned value of stimuli increases attentional dwell time—that is, the time required to disengage attention after it has been captured by the physical salience of the stimulus (Belopolsky et al., 2010; Duncan, Ward, & Shapiro, 1994; Theeuwes, 2010). By this latter account, the learned value of a stimulus does not influence attention at the level of selection but rather at the level of post-selection processing.

In this Chapter, I examine whether an irrelevant and nonsalient distractor, previously associated with reward, captures attention when both stimulus-driven and goal-driven accounts predict that a physically salient and task-relevant target should instead solely determine the locus of attention. Attentional capture by stimuli previously associated with reward here would reveal an involuntary mechanism of attentional selection that is

uniquely value-driven, such that learned value has a direct role in biasing attention as hypothesized in Chapter I.

1. Experiment 3

Experiment 3 mirrored Experiment 1 with the critical difference being that during the test phase, all of the stimuli were differently colored as in the training phase, making the previously reward-associated color nonsalient (one of six colors in the display rather than a color singleton, see Figure 5). Under these conditions, both goal-directed and salience-driven attention mechanisms should bias attention in favor of the target (which is a physically salient shape singleton; see, e.g., Bacon & Egeth, 1994; Theeuwes, 1992, 2010). Attentional capture by the previously reward-associated distractor here would be uniquely consistent with a value-driven mechanism of attentional selection that operates independently of goal-directed and salience-driven mechanisms.

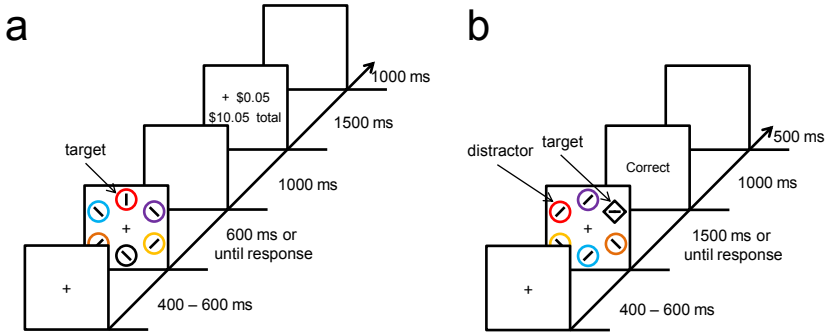


Figure 5. Sequence of events and time course for a trial during training (a) and at test (b) in Experiment 3.

1.1. Methods

1.1.1. Participants. Twenty-six new participants were recruited from the Johns Hopkins community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were provided monetary compensation based on performance (mean = $25.11). Informed consent was obtained from all participants, and all of the

experimental procedures were approved by the Johns Hopkins University Institutional Review Board.

1.1.2. Apparatus and Stimuli. The apparatus and stimuli were identical to that of Experiment 1 with the exception that in the test phase, each item had a unique color. The same colors were used as during training: on distractor-present trials, either red or green (equally-often) replaced one of the nontarget colors.

1.1.3. Design and Procedure. The design and procedure were identical to that of Experiment 1.

1.2. Results and Discussion

Based on the reward contingencies to which participants were exposed during the training phase, trials during the test phase were classified as containing a high-value distractor, a low-value distractor, or neither. A repeated-measures ANOVA revealed that RTs differed significantly among these three conditions, $F(2,50) = 6.07$, $p = .004$ (Figure 6). High-value distractors slowed RT relative to when neither value-related distractor was present, $t(25) = 3.49$, $p = .002$. There was no significant difference in accuracy between the three distractor conditions, $F(2,50) = 0.41$, $p = .667$ (absent: 89.4%, low-value: 89.8%, high-value: 89.2%). These results are striking in that they clearly violate the predictions of both a salience-driven and goal-driven account of attentional capture: the data mirror the well-documented distracting effect of physically salient stimuli (Theeuwes, 1992, 2010; Theeuwes & Godijn, 2002), despite the fact that the distractors were neither physically salient nor goal-relevant, and did not have any identifying features in common with the searched-for target (Folk et al., 1992). Even the fastest 25% of RTs in the high-value distractor condition were slower than those in the distractor absent condition, $t(25) = 3.07$, $p = .005$, suggesting that the high-value distractor captured attention consistently, rather than on only a small proportion of the trials (Yantis, Meyer, & Smith, 1991).

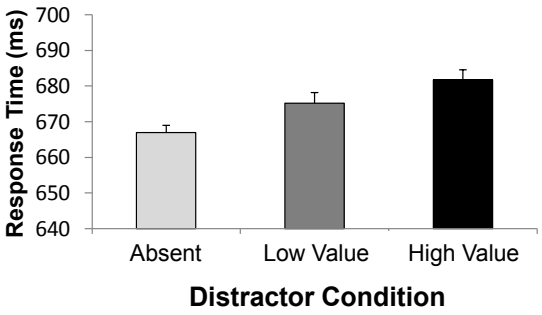
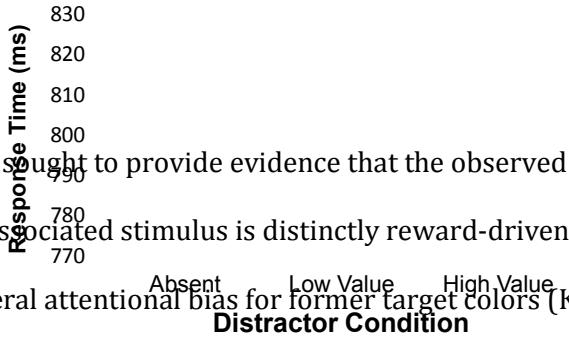


Figure 6. Mean response time ± within-subjects s.e.m. for each distractor condition in the test phase of Experiment 3.



2. Experiment 4

As in Chapter II, I sought to provide evidence that the observed attentional capture by a previously reward-associated stimulus is distinctly reward-driven and cannot be explained by a more general attentional bias for former target colors (Kyllingbaek et al., 2001; Shiffrin & Schneider, 1977). Therefore, I tested a different set of participants who engaged in the same training and testing phases of Experiment 3, but with no reward feedback during training. Instead, participants were compensated with a flat rate that matched the average earnings of participants in the main experiment ($25). If the attentional capture observed in Experiment 3 is value-driven, we should see no evidence of capture by equally-familiar former target colors that were never associated with reward feedback (i.e., following equally long training in which the reward feedback is omitted).

2.1. Methods

2.1.1. Participants. Ten new participants were recruited from the Johns Hopkins community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were compensated with a flat amount of $25.

2.1.2. Apparatus and Stimuli. The apparatus and stimuli were identical to Experiment 3, with the exception that the feedback display during training only informed participants whether their previous response was correct. Critically, no reward feedback was provided.

2.1.3. Design and Procedure. The design and procedure were identical to Experiment 3, with the exception that no monetary rewards were provided for correct responses.

2.2. Results and Discussion

Removing trial-by-trial reward feedback from the training phase completely abolished any effect of the former target color distractors at test, $t(9) = -0.39$, $p = .707$ (absent: 602 ms, red: 606 ms, green: 593 ms). Nor was there a significant difference in accuracy between the red, green, and no-distractor conditions, $F(2,18) = 2.30$, $p = .139$ (absent: 85.9%, red: 83.1%, green: 84.4%). These findings provide converging evidence that reward outcomes bias attention to select stimuli that are associated with those outcomes.

3. Summary and General Discussion

The experiments in this Chapter establish that nonsalient, task-irrelevant stimuli previously associated with reward interfere with visual search during extinction. This result strongly suggests that reward history is alone sufficient to automatically guide attentional selection, independently of the well-established roles of task-specific goals (e.g., Corbetta & Shulman, 2002; Folk et al., 1992) and physical salience (e.g., Itti & Koch, 2001; Theeuwes, 1992, 2010) in the guidance of attention. A control experiment confirmed that the observed attentional capture was attributable to reward feedback during training, ruling out the persistence of a deliberate attentional strategy as an explanation; this confirms evidence that top-down goals in visual search can be adjusted flexibly within seconds (Anderson & Folk, 2012a, 2014; Lien, Ruthruff, & Johnston, 2010), and further distinguishes value-driven capture from goal-directed attentional deployment.

In a classic investigation of attentional control, Shiffrin and Schneider (1977) reported that following extensive training in search for a specific target letter, that letter subsequently captures attention even when it is no longer task-relevant. However, this effect required a great deal of consistent training. The significant slowing caused by value-

driven attentional capture reported here required substantially less training. Furthermore, if reward was omitted during training, the effect disappeared. Value-driven attentional capture is clearly a distinct phenomenon.

The findings reported here provide clear evidence that arbitrary stimuli capture attention involuntarily and persistently as a result of learned associations with reward outcome. Unlike in Chapter II, the distraction caused by previously reward-associated stimuli cannot be explained as resulting from attentional orienting based on physical salience. Because the target was the most physically salient stimulus in these experiments and was currently goal-relevant, it is clear that value-driven attention is not only independent of salience-driven and goal-directed attention but is also capable of out-competing these attention mechanisms under certain conditions, having a powerful and automatic influence on visual processing.

Chapter IV: Spatial Specificity of Value-driven Attentional Capture

Material from this chapter was originally published in:
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Anderson, B. A., & Yantis, S. (2012). Value-driven attentional and oculomotor capture during goal-directed, unconstrained viewing. *Attention, Perception, and Psychophysics, 74*, 1644-1653.

Chapter III showed that stimuli previously associated with reward involuntarily slow response time in target identification, consistent with value-driven attentional capture. The same logic has been used to argue for attentional capture by physically salient stimuli (e.g., Theeuwes, 1992, 1994). However, such slowing can also be explained by non-spatial distraction that does not necessarily involve attentional selection. For example, ignoring physically salient stimuli can entail a non-spatial slowing of visual processing referred to as a filtering cost (Treisman, Kahneman, & Burkell, 1983). It is also possible that the presence of previously reward-associated distractors elicits an increase in arousal that interferes with visual processing independently of attention. Compelling evidence for attentional selection of the previously reward-associated stimuli would come from measures that demonstrate spatially-specific processing of the distractor location.

Two specially-specific markers of attentional processing that have been used to argue in favor of attentional capture by both physically salient stimuli and goal-relevant stimuli (i.e., contingent capture: Folk et al., 1992) are inhibition of return (e.g., Pratt & McAuliffe, 2002; Theeuwes & Godijn, 2002) and oculomotor capture (e.g., Ludwig & Gilchrist, 2002, 2003; Theeuwes et al., 2003). In Experiments 5 and 6, I provide parallel evidence for value-driven attentional capture using these same measures.

1. Experiment 5

When attention is withdrawn from a stimulus, subsequent inhibition of the formerly attended location can be observed, which is believed to prevent repetitive selection

patterns (Posner, Rafal, Choate, & Vaughan, 1985). Such inhibition is referred to as inhibition of return (IOR). If the slowing of response time observed in Chapters II and III is indeed a consequence of spatially-specific attentional selection of the distractor, IOR should result from the need to shift attention from the distractor location to the target location in order to perform the target identification task. In a rapid-trial design such as the one I have employed, IOR should be detectable on the subsequent trial if present. This would manifest as a slowing of response time on trials in which the target appears in the location occupied by a distractor on the prior trial, as processing of the target location would be affected by IOR. Using this logic, I explicitly tested for evidence of IOR using a similar experimental design to Experiment 3. To further extend the findings of that prior experiment and investigate the robustness of value-driven attentional capture, I also employed a considerably shorter training phase (240 vs. 1008 trials) to see whether value-driven attentional priority is evident following a brief training procedure.

1.1. Methods

1.1.1. Participants. Twenty-four new participants were recruited from the Johns Hopkins community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were provided monetary compensation based on performance (mean = $13.24).

1.1.2. Apparatus and Stimuli. The apparatus and stimuli were identical to Experiment 3.

1.1.3. Design and Procedure. The design and procedure were identical to Experiment 3, with the following exceptions. The experiment consisted of a single one-hour session. The training and test phases consisted of 240 trials each, with a short break every 120 trials. Trials terminated after 800 ms in the training phase and 1200 ms in the test phase. High and low rewards were increased to 10¢ and 2¢, respectively.

1.2. Results and Discussion

Closely replicating the critical results from Experiment 3, previously reward-associated distractors slowed visual search in the test phase, despite the shorter training, repeated-measures ANOVA: $F(2,46) = 5.17$, $p = .009$ (Figure 7). Next, I tested whether value-driven attentional capture produces IOR, which would be consistent with spatially-specific processing of the distractor location. To this end, I examined RTs in trials on which no distractor was presented that were preceded by a trial containing a high-value distractor. Responses were on average 66 ms slower when the target appeared in a location formerly occupied by a high-value distractor than when it appeared in another location, $t(23) = 3.13$, $p = .005$, confirming that high-value distractors indeed capture attention in a spatially specific manner. The magnitude of this location-specific interference was somewhat larger than typical demonstrations of IOR (e.g., Posner et al., 1985), suggesting potential differences in the underlying mechanism that are specific to reward-based processing. In

ıditions (all *p*s > .25).

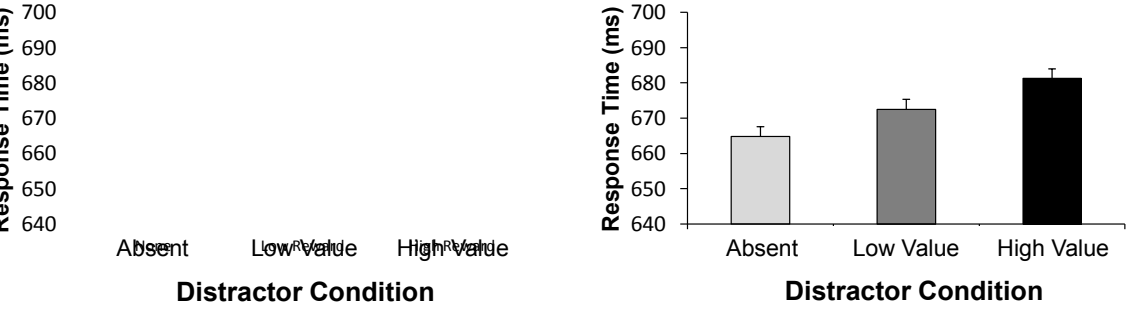

Figure 7. Mean response time ± within-subjects s.e.m. for each distractor condition in the test phase of Experiment 5.

2. Experiment 6

Shifts of covert attention precede and direct overt eye movements (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), such that eye movements occur to the location of highest attentional priority (e.g., Thompson & Bichot, 2005). Although a stimulus

can be spatially attended without a resultant eye movement toward that stimulus, an eye movement toward a stimulus cannot be generated without first attending to that stimulus in a spatially-specific manner (e.g., Thompson & Bichot, 2005). Compelling evidence for spatially-specific attentional capture by previously reward-associated stimuli would be found if participants were to direct eye movements toward such stimuli even though they are entirely irrelevant to the current task and physically nonsalient. In Experiment 6, participants performed a similar task to the prior experiment with eye position monitored.

2.1. Methods

2.1.1. Participants. Fifteen new participants were recruited from the Johns Hopkins University community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were provided monetary compensation based on performance that ranged from $23 to $27 (mean = $25.53). Eye position could not be calibrated for one participant, so all eye tracking results include fourteen participants.

2.1.2. Apparatus. A Mac Mini equipped with Matlab software and Psychophysics Toolbox extensions was used to present the stimuli on a Dell P991 monitor. The participants viewed the monitor from a distance of 75 cm in a dimly lit room, using a chin rest. Manual responses were entered by participants using a standard 101-key US layout keyboard. Eye tracking and pupillometry were performed using an EyeLink 1000 system.

2.1.3. Experimental Task.

2.1.3.1. Training phase. The sequence and timing of events in the training phase is shown in Figure 8a. Each trial consisted of a fixation display for 2000 ms, a search display for 1000 ms, a blank screen for either 1000 or 3000 ms (equally often), a reward feedback display for 1500 ms, and a blank inter-trial interval for 500, 2500, or 4500 ms (exponentially distributed with 500 ms occurring most often). Targets in the training phase were defined as the red or green circle among differently colored circles (blue, cyan, pink,

orange, yellow, or white); exactly one target was present on each trial. The six circles were 2.5° visual angle in diameter, and were placed 6.0° center-to-center from fixation. The training phase consisted of 5 blocks of 60 trials in which each target color appeared in each of the six stimulus positions equally often across trials. Participants reported whether an oriented bar within the target stimulus was either vertical or horizontal by pressing the "z" and "m" keys, respectively. Correct responses were followed by monetary reward feedback, which varied probabilistically with the color of the target. One target color was associated with an 80% probability of a high reward of 15¢ and a 20% probability of a low reward of 3¢; for the other target color, this mapping was reversed. Training thus imbued one color

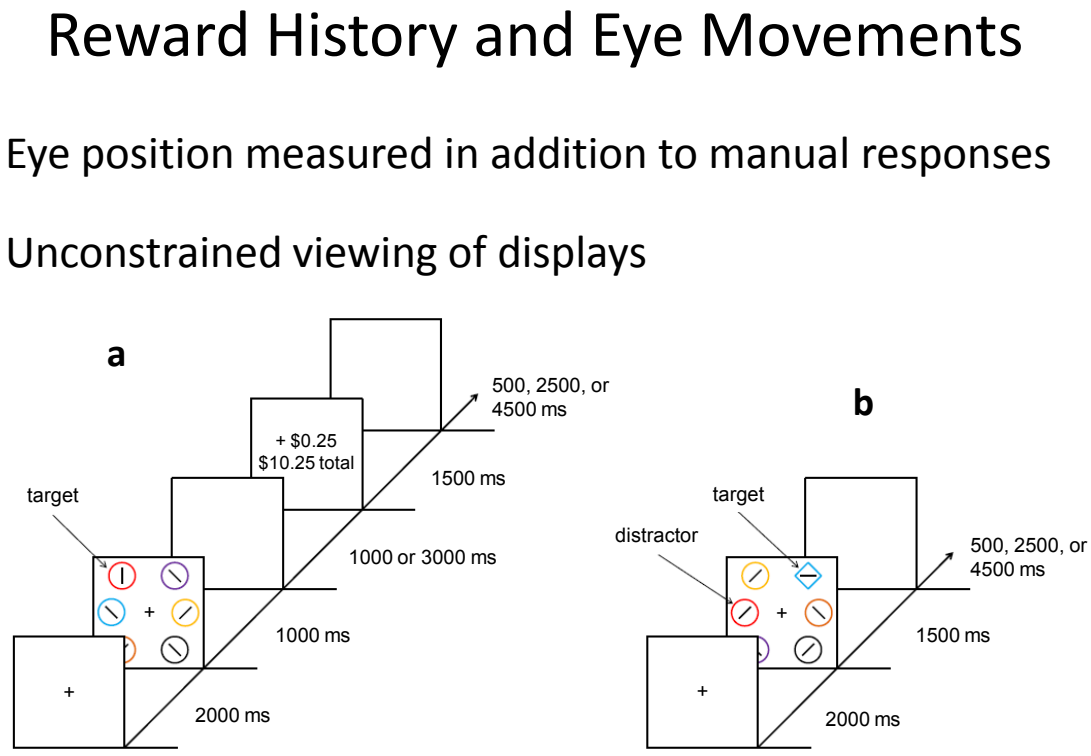

Figure 8. Sequence of events and time course for a trial during training (a) and at test (b) in Experiment 6.

2.1.3.2. Test phase. The sequence and timing of events in the test phase is shown in Figure 8b. Each trial consisted of a fixation display for 2000 ms, a search display for 1500

ms, and a blank inter-trial interval for 500, 2500, or 4500 ms (exponentially distributed with 500 ms occurring most often). Targets in the test phase were now defined as the unique shape, either a circle among diamonds or a diamond among circles (equally often and randomly ordered). Participants made the same judgment concerning the oriented bar contained within the target stimulus. The search items were differently colored, as in the training phase; however, the targets were never red or green. On a randomly-selected one-quarter of the trials, one of the nontarget items was rendered in red and on another one-quarter, one of the nontarget items was rendered in green—these constituted the formerly rewarded *distractors* (the remaining items will be referred to as *nontargets*). The test phase consisted of 4 blocks of 80 trials in which the target appeared in each of the six stimulus positions with equal probability. When a distractor was present, it appeared in each of the five nontarget positions with equal probability. No monetary feedback was provided in the test phase; participants were informed of their accuracy for each block following the completion of that block.

2.1.4. Instructions. Throughout the experiment, participants were encouraged to respond with a button press as quickly as possible while minimizing errors. Participants were instructed to ignore color during the test phase, and to focus on identifying the line orientation within the unique shape. They were provided written and verbal descriptions of the task and procedures prior to each phase of the experiment, and were shown example displays. Participants were neither encouraged nor discouraged from moving their eyes; all they were told was that their eyes would be monitored during the task using a camera.

2.1.5. Eye Tracking. Eye tracking was performed at a sampling rate of 500 Hz. Nine-point calibration was used. Calibration was checked at the beginning of each block and recalibrated as necessary. Head position was maintained using a chin rest, and eye position was measured without applying online drift correction. Saccadic eye movements were

defined as those for which velocity exceeded 30°/sec and acceleration exceeded 8000°/sec. The first eye movement for each search display was measured as the first saccade exceeding one degree visual angle that occurred at least 100 ms following the onset of the search array.

2.1.6. Data Analysis. Manual RTs on error trials and RTs more than three standard deviations above or below the mean of their respective conditions for each participant were excluded from the RT analysis (together this resulted in the removal of 6.5% of the trials). Saccades occurring less than 100 ms following the onset of the search array were considered anticipations and were not included in the eye movement analysis; this resulted in the removal of less than 1% of all initial saccades. Blinks were eliminated by trimming samples spanning 100 ms (50 samples) both before and after the pupils were lost by the eye tracker.

2.2. Results and Discussion

2.2.1. Manual response time and accuracy. I first examined evidence that the previously rewarded distractors captured covert attention in the test phase. Participants were significantly slower to respond to the target line orientation contained in the shape singleton when a high-value distractor was present compared to when no distractor was present, $t(14) = 2.34$, $p = .035$, $d = .60$ (Figure 9); the low-value distractor produced an intermediate degree of slowing, $t(14) = 1.83$, $p = .088$, $d = .47$. This replicates the response time slowing demonstrated in the prior experiments presented in this and earlier chapters. A value-driven impairment in performance was evident for the high-value distractor in accuracy as well, with the low-value distractor again producing an intermediate degree of impairment, $t(14) = 3.15$, $p = .007$, $d = .81$, and $t(14) = 1.07$, $p = .302$, $d = .28$, respectively (absent: 95.1%, low-value: 94.0%, high-value: 92.8%).

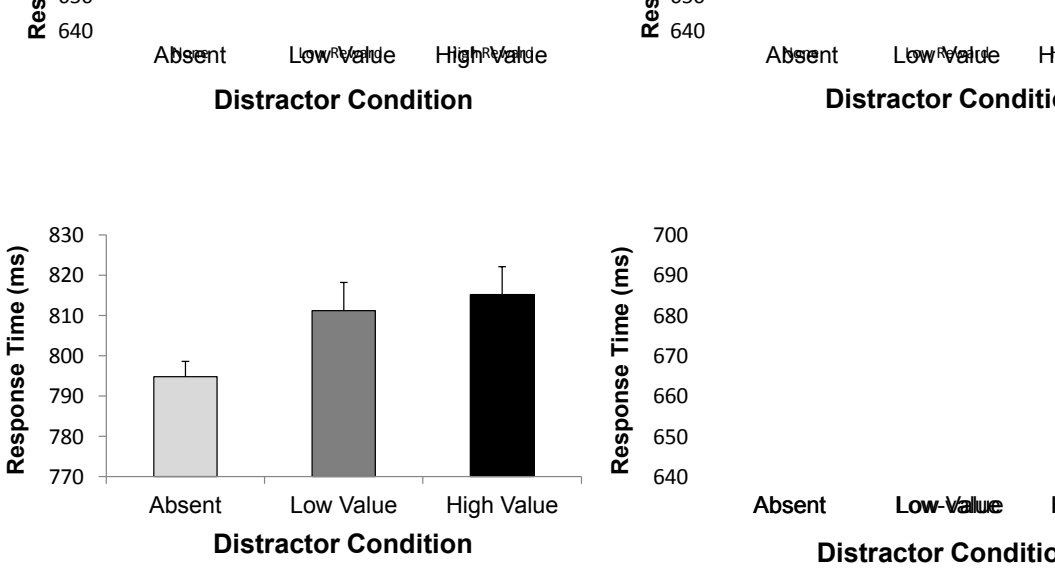

Figure 9. Mean response time ± within-subjects s.e.m. for each distractor condition in the test phase of Experiment 6.

2.2.2. Eye movements. Overall, participants moved their eyes from fixation on 88% of the trials in the test phase. However, there were substantial individual differences in the number of trials on which a saccade occurred; some participants moved their eyes on as many as 100% of the trials and others on as few as 63% of the trials. The occurrence of saccadic eye movements was generally associated with poorer task performance: participants who made fewer initial saccades tended to respond faster, $r = .553$, $p = .040$, and more accurately, $r = -.571$, $p = .033$, than those who made more frequent initial saccades. Across all trials, participants produced slower and less accurate manual responses on trials in which they moved their eyes compared to when they remained fixated, mean RT difference = 112 ms, $t(760.9) = 14.61$, $p < .001$, $d = .58$ (t-test corrected for inhomogeneity of variance), mean accuracy difference = 3.1%, $\chi^2(1) = 8.31$, $p = .004$, $\varphi = .043$, respectively. This outcome shows that eye movements were not required to perform the task well. Participants were no more likely to break fixation when a formerly rewarded distractor was present than when it was absent, mean difference < 1 trial, $t(13) = 0.52$, $p = .612$.

Trials on which a saccade occurred were analyzed in order to assess how these movements were influenced by formerly rewarded distractors. The direction of the first saccade on each trial was analyzed according to whether a distractor was present, and if so,

whether it appeared on the same side of the display as the target or not (the effects reported below did not depend on whether the high-reward target color was red or green, $F(4,48) = 1.06$, $p = .385$, so further analyses collapsed across this variable). The side of the display to which an initial saccade was directed was influenced by the presence and relative location of a formerly rewarded distractor (Figure 10), as indicated by a significant ANOVA, $F(4,52) = 11.79$, $p < .001$, $\eta_p^2 = .476$.

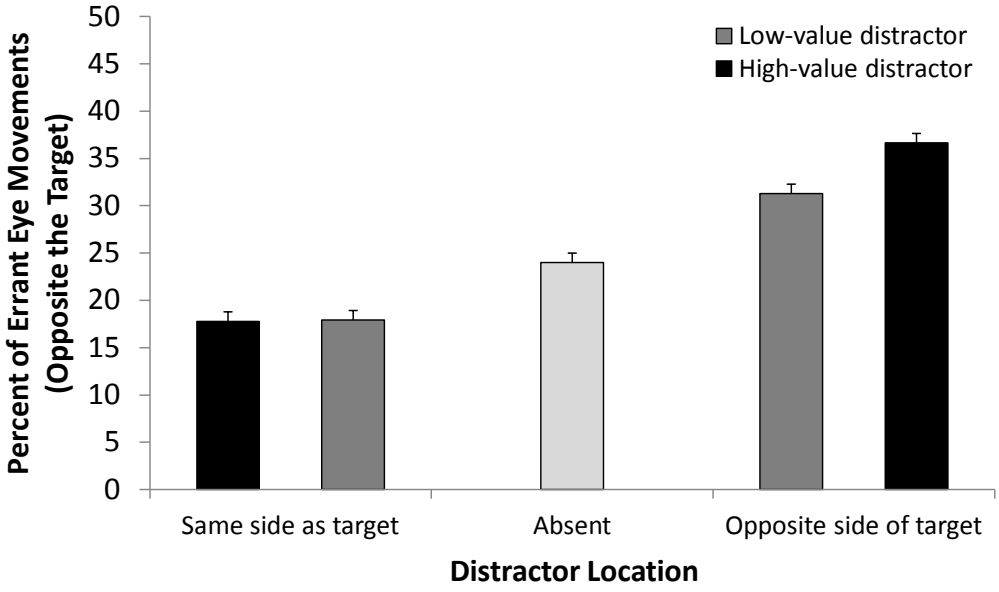

Figure 10. Percent of initial eye movements to the side of the display opposite the target by distractor condition in the test phase of Experiment 6.

I focused my next analyses specifically on trials on which the distractor and target were presented on opposite sides of the visual field and thus competed for the direction of a saccade. Post-hoc contrasts revealed that participants were more likely to make an initial saccade to the side of the visual field opposite the target when a high-value distractor was present on that side compared to when it was absent, $t(13) = 5.57$, $p < .001$, $d = 1.49$, while the low-value distractor produced an intermediate level of such oculomotor impairment, $t(13) = 1.87$, $p = .084$, $d = .50$; this is an indication of value-driven oculomotor capture. Even in the last block of trials, the decrement in saccadic accuracy caused by the high- and low-

value distractors was still evident, $t(13) = 2.48$, $p = .028$, $d = .66$, indicating that value-driven oculomotor capture was persistent. The behavioral impairment in RT caused by the formerly rewarded distractors was still evident when participants did not move their eyes to the side of the visual field containing the distractor, $t(13) = 2.33$, $p = .037$, $d = .63$, indicating that value-driven attentional capture does not necessarily result in value-driven oculomotor capture. However, value-driven oculomotor capture was associated with a large cost in RT such that responses were 80 ms slower when participants looked at the distractor, $t(13) = 4.21$, $p = .001$, $d = 1.04$, indicating that value-driven oculomotor capture substantially impaired performance. For trials on which the distractor and target were presented on the same side of the visual field, participants were also more likely to make their initial saccade to the side of the visual field containing the target when a high-value distractor or a low-value distractor was also present on that side compared to when it was absent, $t(13) = 2.76$, $p = .016$, $d = .74$, and $t(13) = 3.63$, $p = .003$, $d = .97$, respectively.

In order to determine whether this measure of value-driven oculomotor capture reflected a spatially-specific effect of distraction, the number of initial saccades falling within one degree visual angle of the target, a high- or low-value distractor, and a nontarget stimulus was measured on distractor-present trials. The probability of looking at a nontarget stimulus was defined as the probability of initially fixating any nontarget stimulus divided by the number of nontarget stimuli present in the display (4 nontargets on distractor-present trials). This analysis revealed that initial fixations occurred to the target 46% of the time, to the formerly rewarded distractor 22% of the time, and to any given nontarget stimulus 8% of the time. The probability of fixating a distractor was significantly greater than the probability of fixating any given nontarget stimulus, $t(13) = 5.26$, $p < .001$, $d = 1.40$, and this difference was evident even in the last block of trials, $t(13) = 2.40$, $p = .032$, $d = .64$. Taken together, the findings from Experiment 6 provide strong evidence that

previously reward-associated stimuli automatically attract eye movements, which is uniquely consistent with spatially-specific attentional capture by these distractors rather than a non-spatial explanation for their impairment in task performance.

3. Summary and General Discussion

Salient and goal-related stimuli both elicit IOR (e.g., Pratt & McAuliffe, 2002; Theeuwes & Godijn, 2002) and oculomotor capture (e.g., Ludwig & Gilchrist, 2002, 2003; Theeuwes et al., 2003). Although the data from prior chapters reveal an impairment in target processing, as measured by a slowing of response time in target identification caused by a previously reward-associated stimulus, this impairment could be explained by non-spatial forms of distraction that do not imply attention orienting, such as a filtering cost (Treisman et al., 1983). The present results reveal that stimuli imbued with value via reward learning produce IOR and draw eye movements involuntarily, even when they are inconspicuous, not task-relevant, and currently unrewarded. These findings provide strong evidence that, like physically salient and goal-relevant stimuli, previously reward-associated stimuli capture attention in a spatially-specific manner. The findings from this chapter bolster the argument for a third mechanism of attentional control that is independent of the well-documented salience-driven and goal-directed mechanisms as outlined in Chapter I.

The findings from Experiment 6 also provide insight into automatic eye movements more generally. Experiment 6 demonstrates value-driven oculomotor capture even though eye movements were neither encouraged nor required to perform the experimental task, which differs from previous studies of oculomotor capture in which an eye movement to the target was required (Ludwig & Gilchrist, 2002, 2003; Hickey & van Zoest, 2012; Theeuwes et al., 2003; Van der Stigchel & Theeuwes, 2005). This suggests that, at least in the case of oculomotor capture by valuable stimuli, saccades to stimuli with sufficiently high

attentional priority cannot easily be suppressed. This finding has implications for theories of oculomotor control during naturalistic eye movements, as it implies that oculomotor capture can occur as the result of an involuntary process of selection that does not critically depend on the voluntary initiation of an eye movement.

Chapter V: Persistence of Value-driven Attentional Capture

Material from this chapter was originally published in:
Anderson, B. A., & Yantis, S. (2013). Persistence of value-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 6-9.

1. Experiment 7

In all of the experiments presented thus far, value-driven attentional capture has been assessed very soon after the reward training took place. Thus, it is unknown how long the learned biases that underlie value-driven attentional capture persist, and whether these biases eventually extinguish in the absence of continued reinforcement. This is an important theoretical question with implications for our understanding of the mechanisms that underlie how reward learning modifies attentional priority.

One possibility is that value-driven attentional biases are plastic and constantly evolve to reflect only recent reward history. According to such a mechanism of attentional control, only consistently reinforced patterns of attention allocation persist for extended periods of time. Another possibility is that reward learning creates enduring changes in attentional priority that can persist indefinitely without further learning. According to this mechanism of attentional control, organisms maximize their ability to capitalize on prior learning in the guidance of attention, at the possible expense of maintaining attentional biases that are no longer useful. In the present experiment, I provide evidence for a strikingly robust and persistent attentional bias for stimuli as a consequence of reward learning: the effects on attention of the reward trainings used in the experiments presented in Chapters III and IV are evident even several months after the reward learning has taken place, with no additional training.

2. Methods

2.1. Participants

Thirteen individuals from the Johns Hopkins University community were recruited to participate. Six had participated in Experiment 3, and four had participated in Experiment 5, and three had participated in Experiment 6. Eight participants had experienced red as the high-value color in their previous participation, and the other five had experienced green as the high-value color.

Between seven and nine months had elapsed between the initial training phase and participation in the present study. None of these participants had completed any study involving reward since participation in the initial study from which they were recruited. Participants were compensated with $10.

2.2. Apparatus

The apparatus was identical to that of Experiment 1.

2.3. Stimuli, Design, and Procedure

All participants experienced the same sequence of trial events in the present experiment that was used in the test phase of the study they previously participated in (see prior chapters).

2.4. Assessment of Explicit Memory

At the end of the experiment, participants were reminded that they had been rewarded during the original learning phase of a prior experiment for finding red and green colored items, and were asked if they recalled which of the two colors tended to be followed by higher reward than the other. All of the participants reported no memory for which color had been the high-value color.

3. Results

Despite the fact that over half a year had passed since their experience with the training phase, irrelevant but previously reward-associated stimuli still exerted a robust influence on response time in target identification, $F(2,24) = 7.74$, $p = .003$, $\eta_p^2 = .392$ (Figure

stimulus–reward

ıulus was red or green did

,22) = 1.01, p = .380. The

on the specific training

cross these two variables.

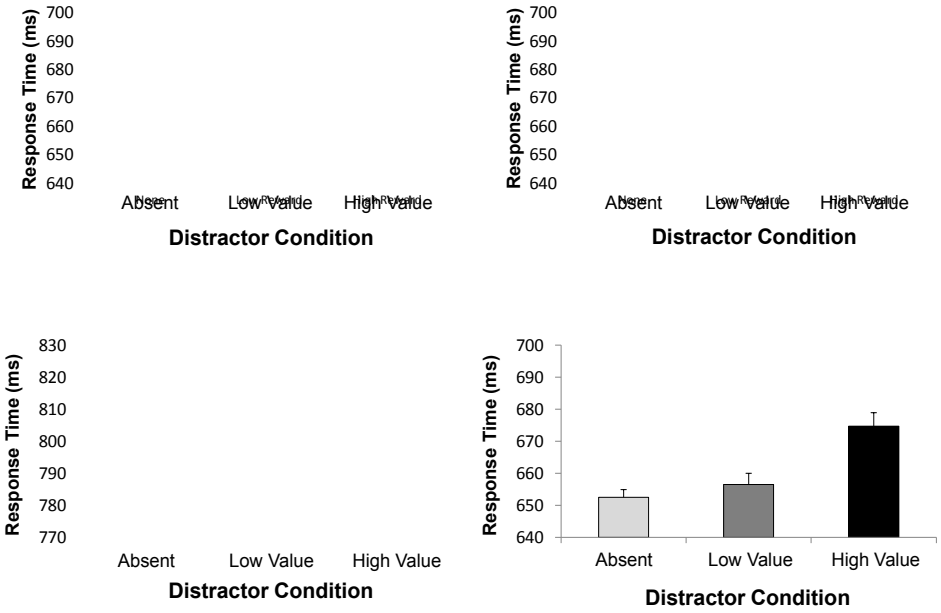

Figure 11. Mean response time ± within-subjects s.e.m. for each distractor condition in the test phase of Experiment 7.

Post hoc comparisons revealed that the formerly high-value stimulus slowed RT both compared to when no formerly-rewarded stimulus was present, $t(12) = 3.79$, $p = .003$, $d = 1.05$, and when a formerly low-value stimulus was present, $t(12) = 2.45$, $p = .031$, $d = .68$. The difference in response slowing in the presence of formerly high- and low-value distractors can only be explained in terms of a difference in learned value, as that is all that differed between the two conditions. Accuracy was high and did not differ significantly among the three distractor conditions, $F(2,24) = 1.24$, $p = .307$, (absent: 92.6%, low-value: 93.1%, high-value: 91.6%).

4. Summary and Discussion

In the present study, I show that stimuli previously associated with reward capture attention as long as 7-9 months following reward learning, without any additional pairings with reward. This suggests that the attentional priorities of the visual system are modified in an enduring way by reward learning, without the updating of such priorities as a function

of their utility. More broadly, the present results suggest that implicit memories are formed between a stimulus and reward that are stored in the brain in such a way that the stimulus will retain a heightened attentional priority whenever it is experienced, leading to the capture of attention.

The magnitude of value-driven attentional capture was greater for high-value than for low-value distractors; this difference was larger here than in prior studies presented in this dissertation. One possible account for this observation is that associations between stimuli and high reward are better remembered and are thus more robust to extinction over extended time periods than associations between stimuli and low reward. Nevertheless, these data show that the reward history associated with visual stimuli is maintained in such a way that it can exert a persistent influence on attentional priority.

Chapter VI: General Conclusions and Theoretical Implications

In Chapter I, I made the argument that attentional selection can be conceptualized in terms of its ability to maximize reward outcomes, such that priority for selection reflects the overall value of the different stimuli in an environment. The stimuli of greatest reward value should be preferentially attended. Although it is clear from the prior literature that rewards influence attention, the extent to which reward history automatically guides attention independently of the current goals of the organism remains unexplored. Indeed, attentional selection has traditionally been conceptualized as reflecting two distinct mechanisms of control: a goal-directed mechanism and a salience-driven mechanism (e.g., Anderson, 2013; Awh, Belopolsky, & Theeuwes, 2012; Corbetta & Shulman, 2002; Theeuwes, 2010).

In this dissertation, I provide evidence that stimuli of learned value automatically capture attention even when they are nonsalient, are known to be task-irrelevant, and are no longer associated with any rewards. I refer to this phenomenon as value-driven attentional capture: automatic attentional selection that is uniquely driven by the learned value of stimuli. Broadly, my findings show that the learning history of an organism with respect to the experience of reward outcomes has a strong and direct influence on attentional selection, via a devoted mechanism that is independent of goal-directed and salience-driven attention mechanisms.

Value-driven attention provides a mechanism by which reward-associated stimuli are selected and processed automatically. Prior to the publication of the work presented in this dissertation, reward was generally thought to modulate attention via voluntary and goal-directed mechanisms, primarily through processes involved in motivated perception (e.g., Kiss et al., 2009; Kristjansson et al., 2010; Navalpakkam et al., 2009, 2010; Pessoa & Engelmann, 2010; Serences, 2008). Such motivated perception mechanisms are likely to

explain, at least in part, how organisms attend to stimuli that are associated with currently sought rewards; however, as I argue in Chapter I, this mechanism would also be likely to result in missed opportunities to obtain reward when the organism is either not expecting these opportunities or is engaged in other goal-directed processing at the time they are encountered. Here, I demonstrate that attention is automatically directed to stimuli as a function of reward history, bypassing the need for goal-directed selection. Thus, prior demonstrations of attention to reward-associated stimuli may reflect a more automatic and less voluntary mode of processing than previously thought. In a broader sense, the results of the present set of studies raise the question of how voluntary and goal-directed human cognition is more generally, a question that has been raised in other domains of cognition as well (Anderson & Folk, 2012a, 2014).

Attention has long been hypothesized to play an important role in reward learning: the strength with which a stimulus–reward association is learned is thought to be a function of how well the stimulus was attended (e.g., Holland & Gallagher, 1999; Pearce & Hall, 1980). The findings presented in this dissertation indicate that reward learning also influences attention. Such value-driven attention may play an important role in facilitating associative reward learning: by automatically directing attention to a stimulus that co-occurs with a reward outcome, the relationship between the two can be learned more quickly and effectively than might be the case if attention were unguided by reward.

The theory of incentive salience predicts that when stimuli are associated with the experience of a reward outcome, these reward cues become motivationally salient and automatically elicit approach behavior (e.g., Berridge, 2012; Berridge & Robinson, 1998; Robinson & Berridge, 2008). In essence, the cue comes to trigger a "wanting" response associated with the desire to obtain the reward it has been linked to. Incentive salience has been used to explain why cues for a drug of abuse can trigger a relapse into substance use

even following long periods of abstinence (e.g., Berridge & Robinson, 1998). In order for a cue to trigger such a wanting response and subsequent approach behavior, however, it must first be processed, presumably requiring attention to the stimulus. Value-driven attention reflects a mechanism that would facilitate such approach behavior by rapidly and automatically prioritizing the processing of reward cues.

Stimuli associated with drugs of abuse (i.e., drug cues) have a powerful ability to automatically capture attention (e.g., Field & Cox, 2008; Lubman, Peters, Mogg, Bradley, & Deakin, 2000), and the magnitude of this capture is predictive of addiction relapse (Field & Cox, 2008; Marissen, Franken, Waters, Blanken, van den Brink, & Hendriks, 2006). This relationship between attention and addiction is consistent with the idea that value-driven attentional selection and cue-triggered wanting are related. The results of the studies presented in this dissertation suggest that attentional biases for drug cues may not be a specific consequence of drug use but rather a consequence of reward learning more generally. Consistent with the relationship between incentive salience and value-driven attention more broadly, I have shown that individuals in treatment for drug addiction are hypersensitive to the influence of non-drug reward on attention (Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013).

Attentional priority to reward-related stimuli will often be adaptive when reward structures are stable, serving to maximize reward procurement. However, an inability to ignore formerly rewarding stimuli that run counter to current behavioral goals, such as unhealthy food in the case of obesity, can be highly maladaptive. Conversely, a tendency to ignore or pay too little attention to reward-related stimuli could be dysfunctional for wellbeing. In this way, the value-based modulation of attention may play a key role in a variety of clinical syndromes in which both attention and reward have been implicated, including drug addiction (e.g., Field & Cox, 2008; Lubman et al., 2000; Marissen et al., 2006),

obesity (e.g., Davis, 2010), attention-deficit hyperactivity disorder (e.g., Bush, 2010), obsessive-compulsive disorder (e.g., Sheppard et al., 2010), depression (e.g., Mathews & MacLeod, 2005), and autism (e.g., Sasson, Elison, Turner-Brown, Dichter, & Bodfish, 2011; Sasson, Turner-Brown, Holtzclaw, Lam, & Bodfish, 2008). Several of these conditions are highly comorbid (e.g., Bush, 2010; Davis, 2010; Sheppard et al., 2010), suggesting a common underlying mechanism that may be related to value-driven attention. More specifically, psychopathology might in part reflect over- or under-prioritization of certain types of reward information by the attention system. Future research using clinical populations could examine the validity of this suggestion, using value-driven attention as a conceptual framework.

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Yantis, S., Meyer, D. E., & Smith, J. E. K. (1991). Analysis of multinomial mixture distributions: New tests for stochastic models of cognition and action. *Psychological Bulletin, 110*, 350-374.

Curriculum Vitae

Brian A. Anderson was born May 17, 1984 at Penobscot Bay Medical Center in Rockport, ME to William and Kristine Anderson. In 2006, he graduated with a B.A. in Social Science from the University of Maine at Augusta, having completed most of his coursework at the University College at Thomaston (which has since relocated to Rockland). Brian then completed a M.S. in Psychology at Villanova University, having conducted studies of visual attention under the mentorship of Dr. Charles Folk (with whom he maintains active collaboration). Upon graduating from Villanova University, Brian entered into the PhD program in Psychological and Brain Sciences under the mentorship of Dr. Steven Yantis, where he completed the works presented in this dissertation along with other studies of human attention.

Brian A. Anderson

Johns Hopkins University

EDUCATION

Ph.D. in Psychological and Brain Sciences 2014
Johns Hopkins University (Expected)
Research Advisor: Dr. Steven Yantis

M.S. in Psychology 2009
Villanova University
Research Advisor: Dr. Charles Folk

B.A. in Social Science 2006
University of Maine at Augusta

AWARDS AND HONORS

G. Stanley Hall Scholar's Award (Johns Hopkins University) 2013
Robert S. Waldrop Junior Investigator's Award (Johns Hopkins University) 2012
Walter L. Clark Fellowship Fund Award (Johns Hopkins University) 2012
Ingeborg L. and O. Byron Ward Outstanding Thesis Award (Villanova University) 2009
Alumni Association Textbook Scholarship (Villanova University) 2008
Travel Award (Villanova University) 2008
Full Graduate Assistantship (Villanova University) 2008
Distinguished Social Science Student (University of Maine at Augusta) 2007
Summa Cum Laude with Honors (University of Maine at Augusta) 2007

SOURCES OF FUNDING

NIH Developmental Pilot Grant P30-MH075673 "*Examining the Role of Attentional Bias on Risk Taking Behavior in HIV+ Patients*" 07/01/2013-06/30/2014. Role: co-investigator (PI: Justin McArthur). Total direct costs: $50,000.

NIH Predoctoral Fellowship F31-DA033754 "*Mechanisms of Value-Driven Attentional Capture*" 06/01/12-05/31/15. PI: Brian A. Anderson. Sponsors: Steven Yantis (primary) and Cherie Marvel. Total direct costs: $126,696.

PUBLICATIONS

Anderson, B. A., & Folk, C. L. (2014). Conditional automaticity in response selection: Contingent involuntary response inhibition with varied stimulus-response mapping. *Psychological Science, 25*, 547-554.

Sali, A. W., **Anderson, B. A.**, & Yantis, S. (2013). Reinforcement learning modulates the stability of cognitive control settings for object selection. *Frontiers in Integrative Neuroscience, 7:95*.

Anderson, B. A., Faulkner, M. L., Rilee, J. J., Yantis, S., & Marvel, C. L. (2013). Attentional bias for non-drug reward is magnified in addiction. *Experimental and Clinical Psychopharmacology, 21*, 499-506.

Anderson, B. A. (2013). A value-driven mechanism of attentional selection. *Journal of Vision, 13(3):7*, 1-16.

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Yantis, S., **Anderson, B. A.**, Wampler, E. K., & Laurent, P. A. (2012). Reward and attentional control in visual search. In M. Dodd & J. Flowers (Eds.) *Nebraska Symposium on Motivation (Vol. 59). The Influence of Attention, Learning, and Motivation on Visual Search*. Lincoln, NE: University of Nebraska Press.

Anderson, B. A., & Folk, C. L. (2012). Dissociating location-specific inhibition and attention shifts: Evidence against the disengagement account of contingent capture. *Attention, Perception, & Psychophysics, 74*, 1183-1198.

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Anderson, B. A., & Folk, C. L. (2010). Variations in the magnitude of attentional capture: Testing a two-process model. *Attention, Perception, & Psychophysics, 72*, 342-352.

Folk, C. L., & **Anderson, B. A.** (2010). Target uncertainty effects in attentional capture: Color singleton set or multiple attentional control settings? *Psychonomic Bulletin & Review, 17*, 421-426.

MANUSCRIPTS SUBMITTED OR IN PREPARATION

Anderson, B. A., Laurent, P. A., & Yantis, S. (submitted). Value-driven attentional priority signals in human basal ganglia and visual cortex.

Anderson, B. A., Leal, S. L., Hall, M. G., Yassa, M. A., & Yantis, S. (submitted). The attribution of value-based attentional priority in individuals with depressive symptoms.

Sali, A. W., **Anderson, B. A.**, & Yantis, S. (submitted). The role of reward prediction in the control of attention.

Moher, J., **Anderson, B. A.**, & Song, J. -H. (submitted). Stimulus-driven control over selection: Dissociable effects of stimulus salience on attention and goal-directed action.

Anderson, B. A. (submitted). Goal-directed attentional selection is imprecise.

Laurent, P. A., Hall, M. G., **Anderson, B. A.**, & Yantis, S. (in preparation). Valuable orientations capture attention.

Harris, A. D., Puts, N. A. J., **Anderson, B. A.**, Yantis, S., Pekar, J., Barker, P. B., & Edden, R. A. E. (in preparation). Multi-regional investigation of the relationship between functional MRI BOLD activation and GABA concentration.

Anderson, B. A., & Yantis, S. (in preparation). Experiencing equal rewards unequally: Evidence for a self-perpetuating bias in reward processing.

CONFERENCE PRESENTATIONS

Anderson, B. A., Faulkner, M. L., Rilee, J. J., Yantis, S., & Marvel, C. L. (2014, May). *Attentional bias for non-drug reward is magnified in addiction*. Poster presented at the annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Sali, A. W., **Anderson, B. A.**, & Yantis, S. (2014, May). *Statistical learning modulates the flexible control of spatial attention.* Poster presented at the annual meeting of the Vision Sciences Society, St. Pete Beach, FL.

Sali, A. W., **Anderson, B. A.**, & Yantis, S. (2013, November). *Statistical regularities modulate the flexibility of attentional control.* Poster presented at the annual meeting of the Psychonomic Society, Toronto, Canada.

Moher, J., **Anderson, B. A.**, & Song, J. -H. (2013, November). *Reward-associated stimuli trigger movement repulsion in goal-directed action.* Poster presented at the annual meeting of the Psychonomic Society, Toronto, Canada.

Anderson, B. A., Faulkner, M. L., Rilee, J. J., Yantis, S., & Marvel, C. L. (2013, October). *Attentional bias for non-drug reward is magnified in addiction*. Poster accepted at the annual National Institutes of Health National Graduate Student Research Conference, Bethesda, MD [conference canceled].

Anderson, B. A., Laurent, P. A., & Yantis, S. (2013, May). *Neural mechanisms of value-driven attentional capture.* Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Sali, A. W., **Anderson, B. A.**, & Yantis, S. (2013, May). *The role of predictable and unpredictable reward in the control of attention.* Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Folk, C. L., & **Anderson, B. A.** (2013, May). *Involuntary inhibition of motor responses contingent on top-down goals.* Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Anderson, B. A., & Yantis, S. (2012, November). *Persistent changes in attentional bias following brief reward learning*. Poster presented at the annual meeting of the Psychonomic Society, Minneapolis, MN.

Sali, A. W., **Anderson, B. A.**, & Yantis, S. (2012, November). *Reinforcement learning modulates preparatory states of cognitive flexibility*. Paper presented at the annual Object Perception, Attention, and Memory (OPAM) conference, Minneapolis, MN.

Anderson, B. A., & Yantis, S. (2012, May). *Value-driven oculomotor capture.* Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Laurent, P. A., **Anderson, B. A.**, Hall, M. G., & Yantis, S. (2012, May). *Value-driven attentional capture by rewarded orientations.* Poster presented at the annual meeting of the Vision Sciences Society, Naples, FL.

Yantis, S., **Anderson, B. A.**, & Laurent, P. A. (2011, April). *Reward, distraction, and attentional control.* Paper presented at the annual meeting of the Society of Experimental Psychologists, Seattle, WA.

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011, November). *On the robustness of value-driven attentional capture.* Poster presented at the annual meeting of the Psychonomic Society, Seattle, WA.

Anderson, B. A., & Folk, C. L. (2011, November). *Negative cuing effects are NOT a signature of attentional capture or disengagement.* Poster presented at the annual meeting of the Psychonomic Society, Seattle, WA.

Anderson, B. A., Laurent, P. A., & Yantis, S. (2010, November). *Reward-driven attentional capture.* Paper presented at the annual meeting of the Psychonomic Society, St. Louis, MO.

Anderson, B. A., & Folk, C. L. (2009, November). *Variations in the magnitude of attentional capture: Testing a two-process model.* Paper presented at the annual Object Perception, Attention, and Memory (OPAM) conference, Boston, MA.

Folk, C. L., & **Anderson, B. A.** (2008, November). *Target uncertainty and attentional capture: Singleton detection mode or multiple top-down control settings?* Poster presented at the annual meeting of the Psychonomic Society, Chicago, IL.

INVITED TALKS AND SYMPOSIA

Anderson, B. A. (2014, February). *Reward Learning and the Value-Driven Control of Attention.* National Institute on Drug Abuse, Baltimore, MD.

Anderson, B. A. (2014, February). *Reward Learning and the Value-Driven Control of Attention.* University of Virginia.

Anderson, B. A. (2014, January). *Reward Learning and the Value-Driven Control of Attention.* Florida State University.

Anderson, B. A. (2013, December). *Reward Learning and the Value-Driven Control of Attention.* University of Nebraska – Lincoln.

Anderson, B. A. (2013, December). *Reward Learning and the Value-Driven Control of Attention.* National Institutes of Health, Bethesda, MD.

Anderson, B. A. (2013, January). *Reward Learning and the Selection of Visual Stimuli.* Clinical Neuroscience Seminar Series, Johns Hopkins University School of Medicine, Baltimore, MD.

Anderson, B. A., & Yantis, S. (2012, July). *A Value-Driven Mechanism of Attentional Selection.* Third international symposium on visual search and selective attention, Munich, Germany.

JOURNAL REVIEWING

Psychological Science
Journal of Neuroscience
Biological Psychology
Cognition
JEP: General
PLOS ONE
Psychonomic Bulletin & Review
*Journal of Vision**
Visual Cognition
Vision Research
Emotion
Psychological Research
Neuropsychopharmacology
JEP: Human Perception & Performance
Attention, Perception, & Psychophysics
Frontiers in Human Neuroscience
Experimental Brain Research
Canadian Journal of Experimental Psychology
Behavior Research Methods
British Journal of Psychology

*Awarded *Exceptionally Good Review* (x3)

JOURNAL EDITING

Special Issue of *Visual Cognition*: Reward Guides Visual Attention: Selection, Learning and Motivation. Brian A. Anderson, Leonardo Chelazzi, Steven Yantis, & Jan Theeuwes (Eds.). Expected date of publication: early 2015.

PROFESSIONAL MEMBERSHIPS

Vision Sciences Society
Association for Psychological Science

TEACHING EXPERIENCE

Johns Hopkins University

Instructor:	*Laboratory in the Analysis of Psychological Data*
Co-instructor:	*Advanced Statistical Methods (BAA 3 of 22 lectures)*
Co-organizer:	*Functional Neuroimaging Seminar (2 semesters)*
Teaching Assistant:	*Advanced Statistical Methods, Functional Human Neuroanatomy, Positive Psychology*

Villanova University
Instructor: *Laboratory in Cognition (2 sections)*

University of Maine at Augusta
Teaching Assistant: *Abnormal Psychology, Interviewing and Counseling*